LONGITUDINAL DYNAMICS STUDIES AT ALBA

HEPS-ALBA meeting - 13/07/2026

Ignasi Bellafont

OUTLINE

- **Introduction:** ALBA and ALBA II Light Sources
- **ALBA II RF system:** Overview
- **Beam stability studies:** Tracking simulations, foreseen solutions
- **Transient beam loading (TBL):** Expected impact, foreseen solutions
- **Trip compensation system (TCS):** Simulations and experimental results
- **Summary**

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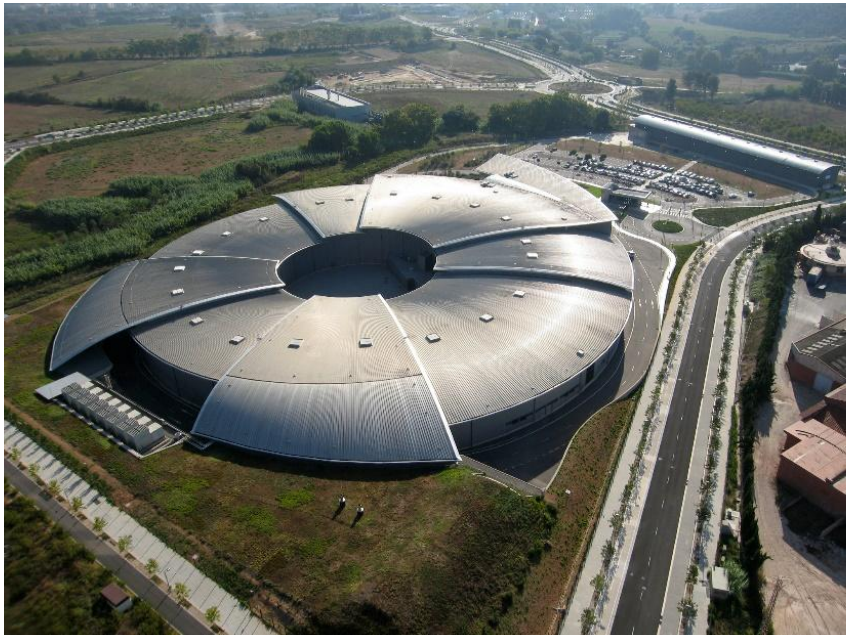
INTRODUCTION – ALBA

- **ALBA** is a **3 GeV**, 3rd generation synchrotron light source located near Barcelona, **Spain**
- User operation since 2012
- **13 beamlines** currently in operation, dedicated to life and material science, solid-state physics. 2 more under construction
- And upgrade towards **4th generation is** planned for 2030, ALBA II

Parameter	Value	Unit
Energy	3.0	GeV
Beam current	250	mA
Circumference	268.8	m
Emittance	4.5	nm·rad
Loses per turn (w/o IDs)	1.02	MeV
Momentum compaction factor	$8.9 \cdot 10^{-4}$	



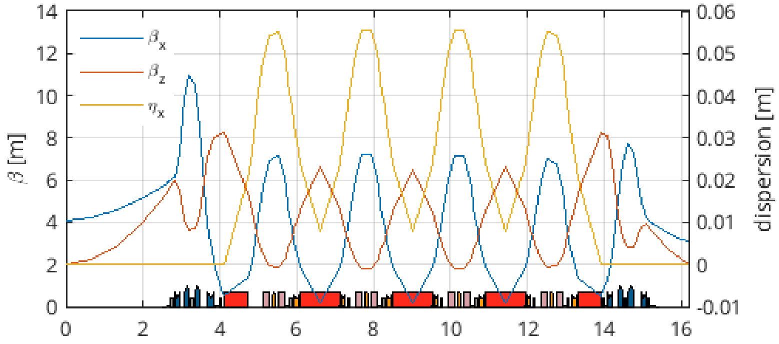
INTRODUCTION - ALBA II

- **ALBA II** will be the upgrade of ALBA, aimed at having a much lower beam emittance (around **22 times lower**)
- The **storage ring** will be replaced, while the booster ring and LINAC will remain unchanged
- Installation and commissioning planed for 2030, **operation** expected in **2032**

Parameter - A2L007E	Value	Unit
Energy	3.0	GeV
Beam current	300	mA
Circumference	268.8	m
Emittance	204.4	pm·rad
Loses per turn (w/o IDs)	0.93	MeV
Momentum compaction factor	$1.08 \cdot 10^{-4}$	
Touschek lifetime 0.5 C	5.4	h

F. Pérez et al., DOI: 10.18429/JACoW-IPAC2025-MOPS043

ALBA II facilities



Optical functions of a single lattice period

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ALBA II RF SYSTEM

- **Booster RF:** Same as in ALBA, 1 x 5-cell PETRA type cavity, fed with a 50 kW BTESA SSPA
- **Storage Ring:** 6 x EU HOM damped NC cavity (same as in ALBA) + **4 x New EU HOM damped NC 3H active cavity.** Fed with 130 kW and 20 kW of SSPA power, respectively

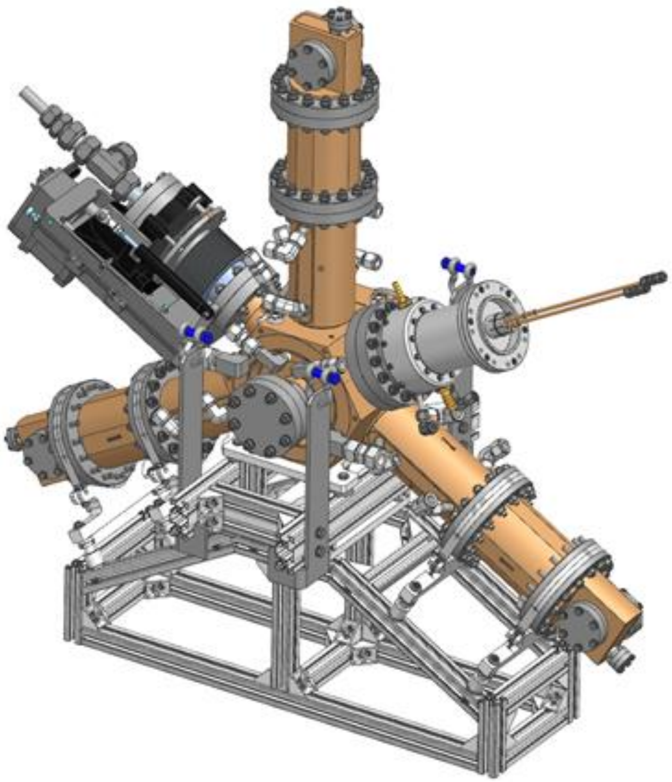
Parameter	Value	Unit
Main RF voltage	2.4	MV
Harmonic RF voltage	680	kV
Number of cavities (MC / HC)	6 / 4	
Main cavity voltage	400	kV
Harmonic cavity voltage	170	kV
Main RF frequency	500	MHz
Harmonic RF frequency	1500	MHz
Bunch lengthening HFP	3.9	
Bunch length HFP	31.7	ps

ALBA II RF system
A2L007E

6x Main NC RF cavity
400 kV - 500 MHz

4x Harmonic NC active RF cavity prototype
170 kV - 1500 MHz

ALBA II RF SYSTEM – 3rd harmonic cavity

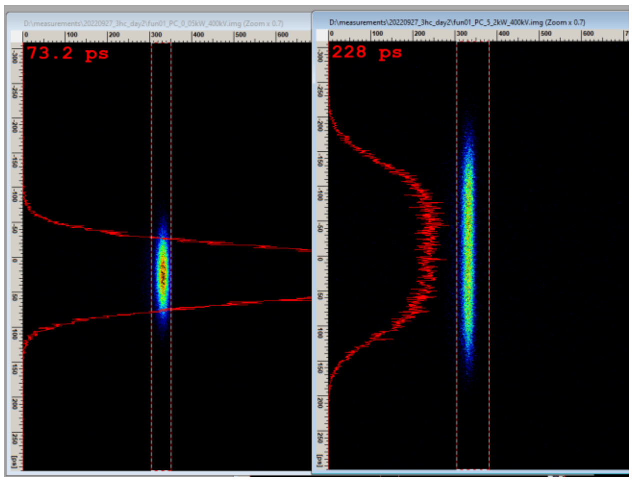


Harmonic NC active RF cavity

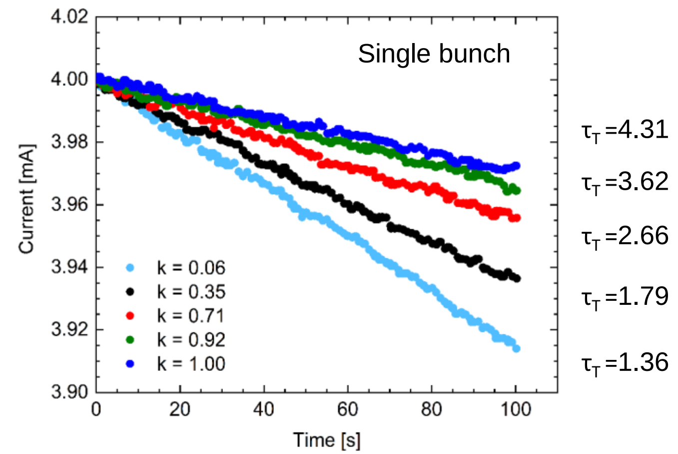
F. Pérez et al., DOI: 10.1016/j.nima.2024.169935
P. Solans et al., DOI: 10.18429/JACoW-IPAC25-WEBD2

- In order to **increase the beam lifetime** of its 4th generation upgrade, ALBA designed **a new active, normal conducting, 3rd harmonic cavity**, based on the EU HOM Damped 500 MHz cavity
- A **prototype was tested** during 2023-2025 at BESSY II, in a collaboration of three institutions (ALBA, HZB and DESSY)
- **Manufacturing** of the definitive cavities is **completed** (5 cavities). The installation will take place this summer. All 2027 will be dedicated to their commissioning and machine studies
- The active feature was chosen in order to i) **maximize** the lengthening **performance** of the doble RF system, due to its TBL and PTBL mitigation capabilities and ii) **smoother operation**, being its voltage and phase independent on the beam current

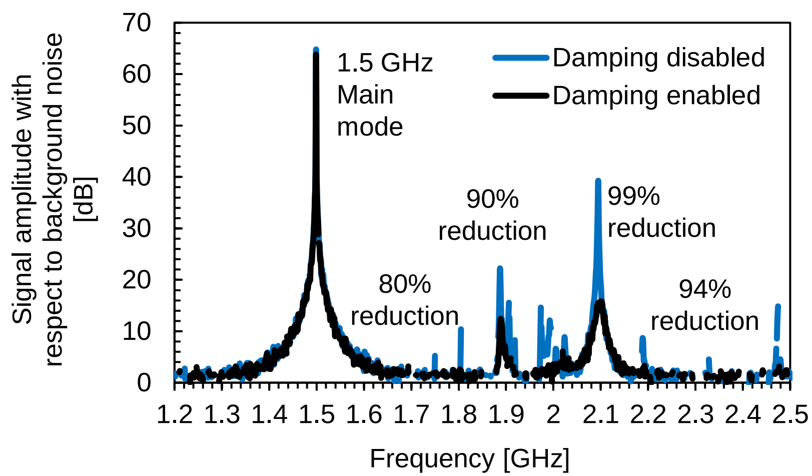
ALBA II RF SYSTEM – 3rd harmonic cavity



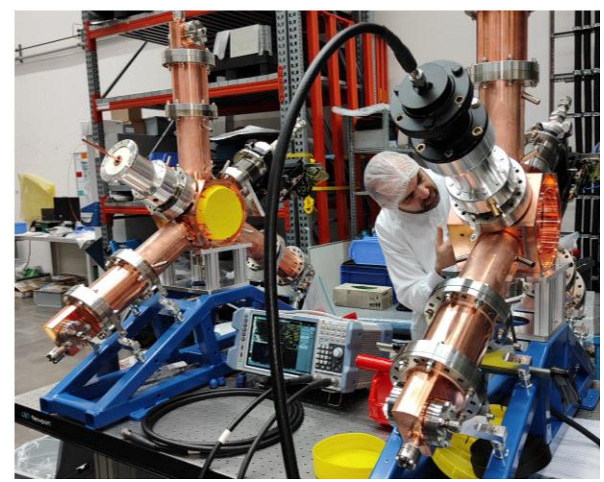
ALBA-HZB-DESY 3HC commissioning



Lifetime measurements with different ratios of 3HC voltage at BESSY II

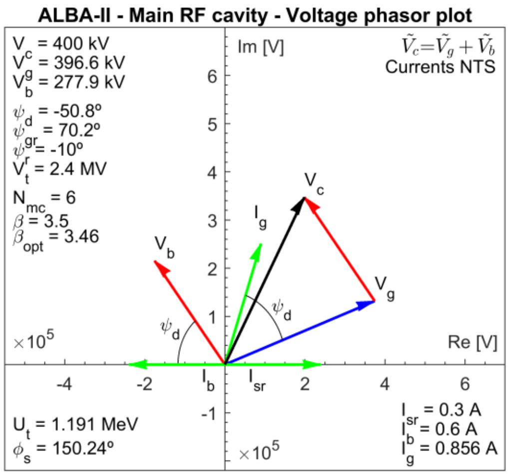


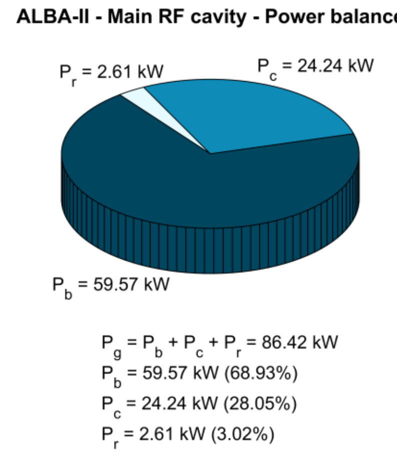
Measurement of cavity voltage spectrum before and after HOM damping activation

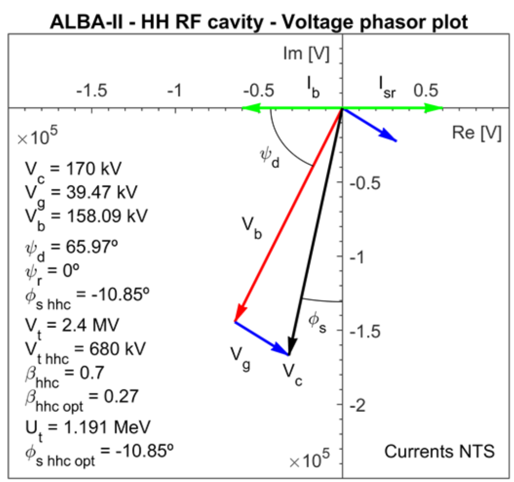


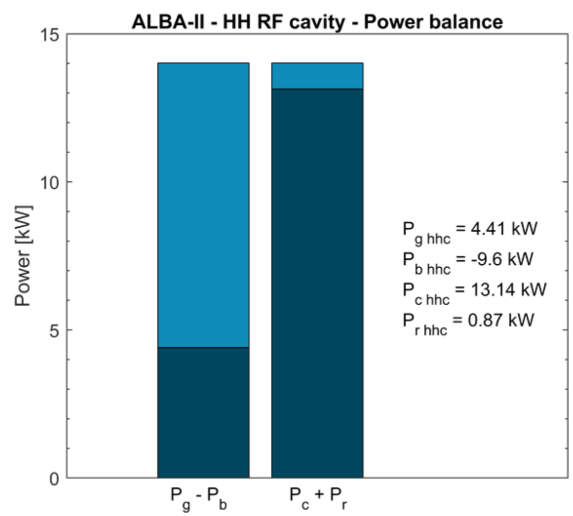
3HC Research Instruments factory test

ALBA II RF SYSTEM









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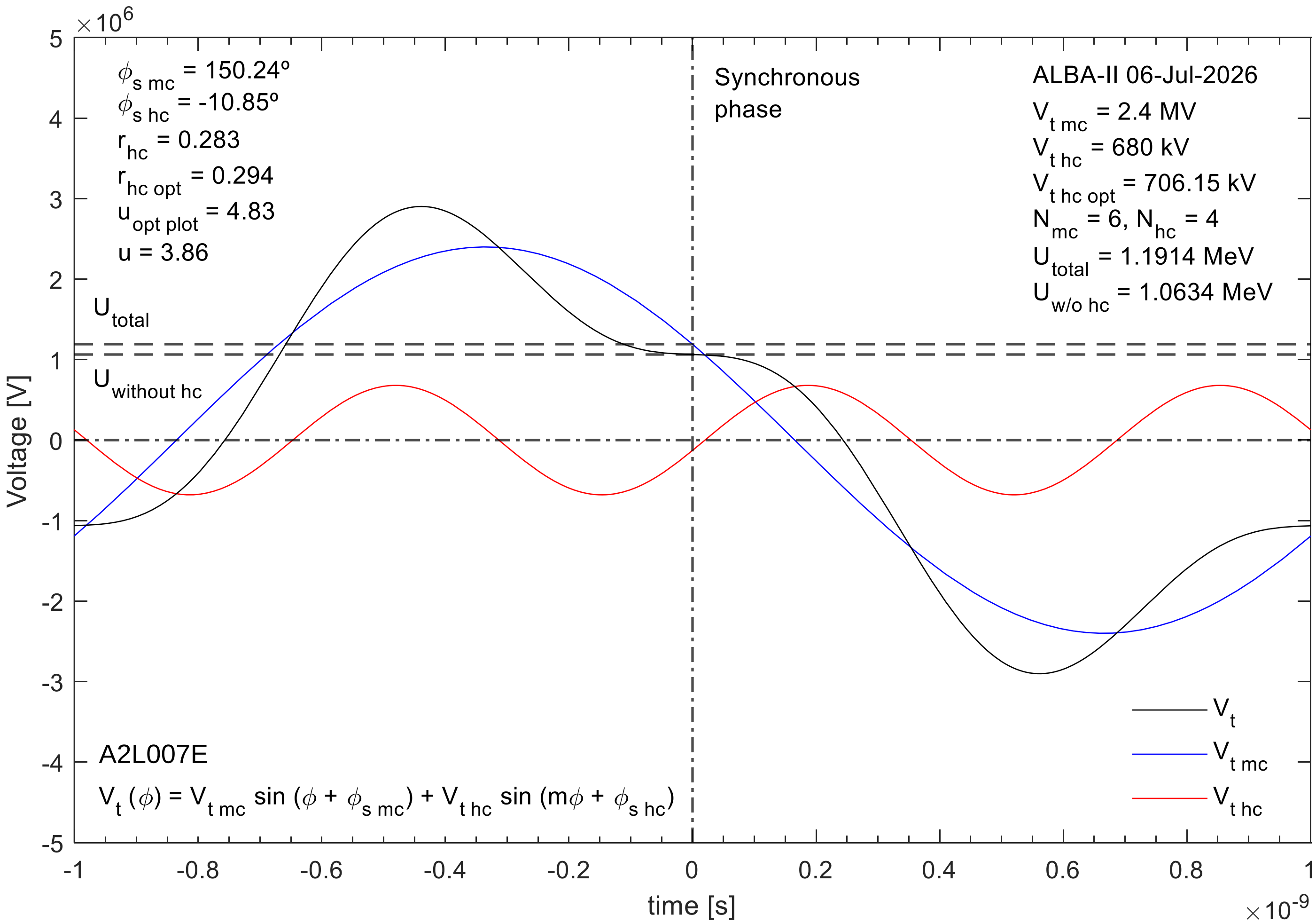
ALBA II RF SYSTEM



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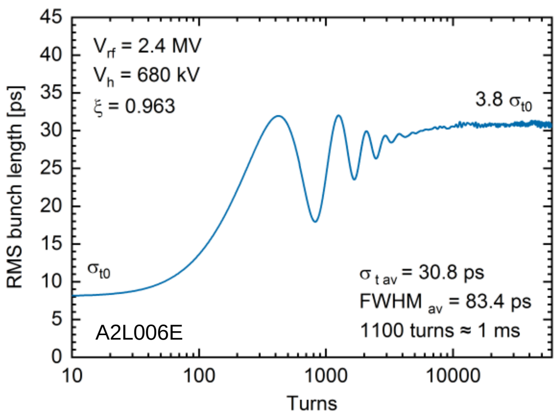
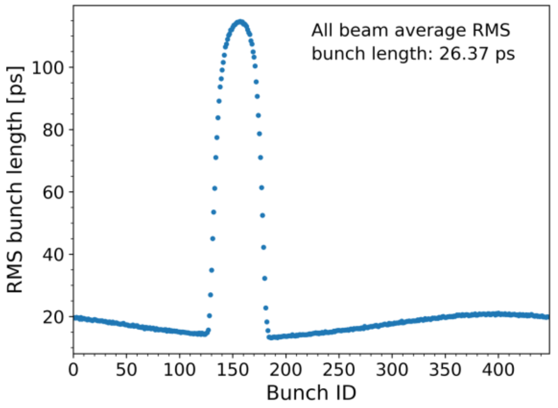
BEAM STABILITY STUDIES – ALBA II

- To evaluate the beam stability due to the double RF system in ALBA II, several **particle tracking simulations** have been carried out using `elegant`
- The simulations include the **RF cavities' impedance**, synchrotron radiation damping, a PI control loop, a linear transformation matrix and quantum fluctuations. At this stage, no additional impedance sources are considered
- The simulation, the bunch shape and phase, cavity voltage, beam energy, and emittances are monitored and used to assess the overall **system stability**
- The simulations predict the onset of **PTBL** instabilities for flatness factors above **ξ = 0.96**. The HC voltage is therefore limited to 680 kV, with 706 kV corresponding to the flat potential (FP) condition
- Currently, we have been testing **mbtrack2** due to its advanced longitudinal dynamics capabilities, particularly its implementation of coherent synchrotron frequency shift calculations and Direct RF Feedback (DRFF)



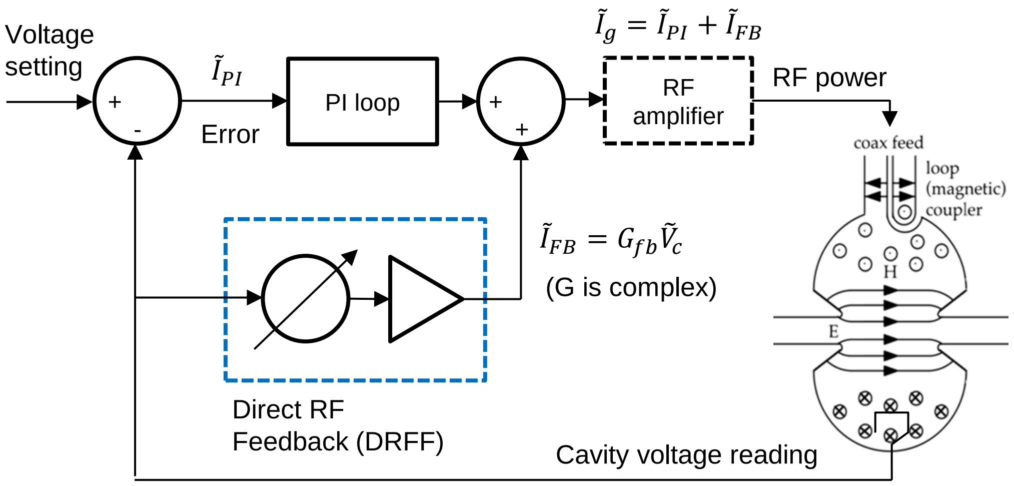
Simulation of the bunch length convergence after the HCs are activated

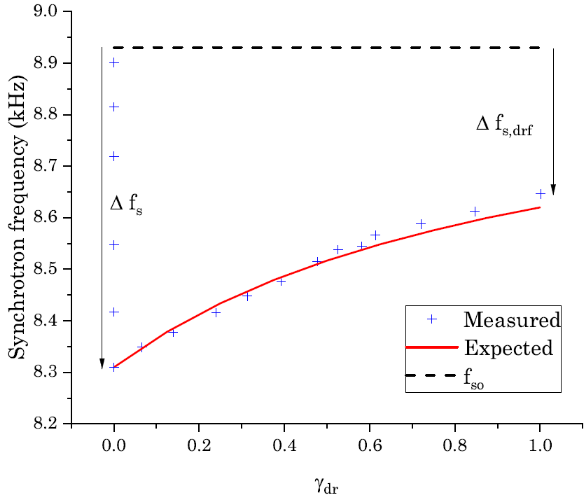


PTBL instabilities example, using FP settings and HFP

BEAM STABILITY STUDIES – DRFF

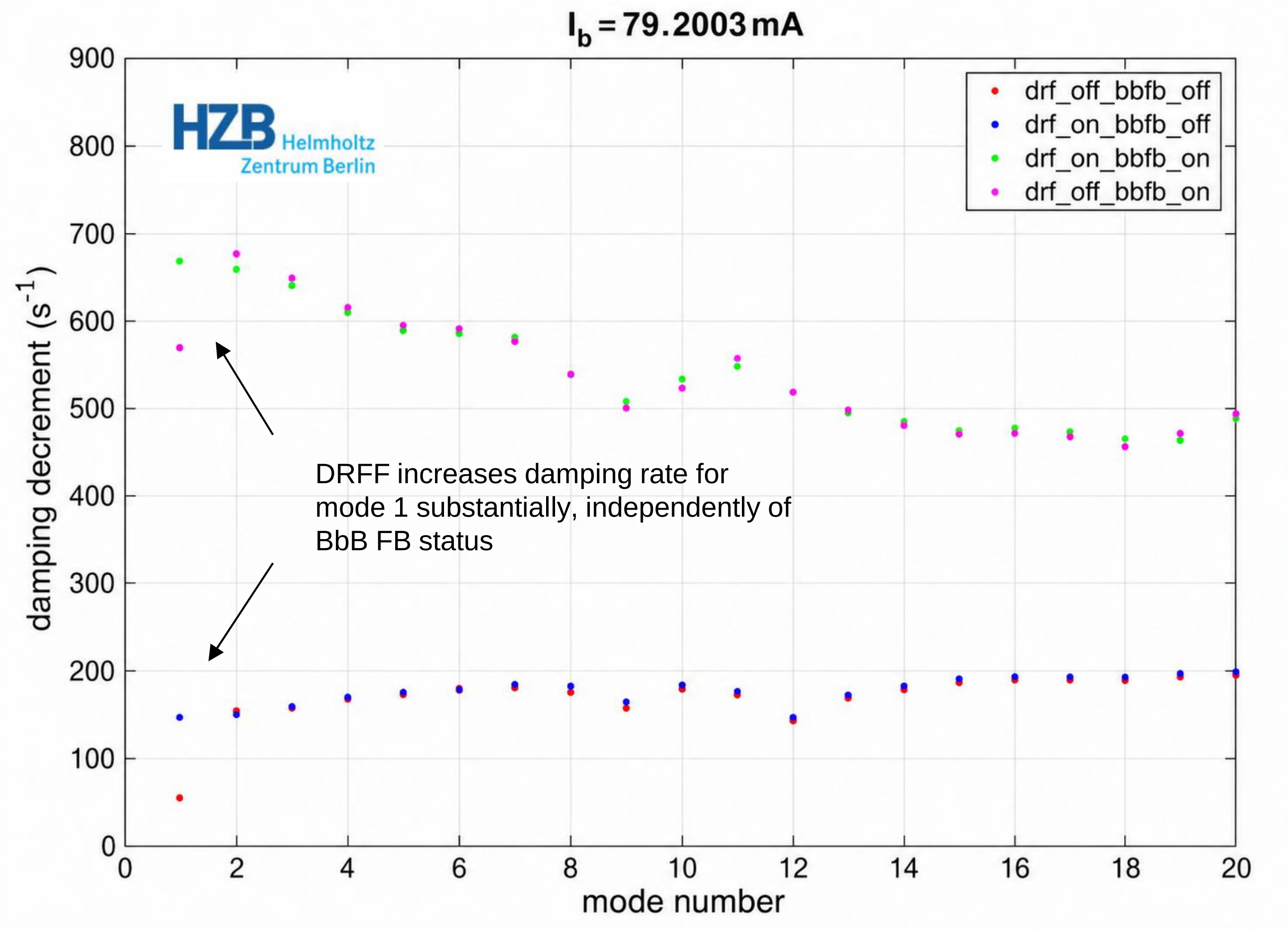
- **DRFF** would improve the bunch lengthening performance of the harmonic system in ALBA II, by virtually lowering the R/Q ratio and then **mitigate** the Periodic Transient Beam Loading (**PTBL**) instability
- DRFF will also allow us to **lower the main voltage** setting in ALBA II, increasing operation reliability and lowering energy consumption
- We have already **implemented and tested** a digital DRFF in the main cavities achieving virtual R/Q reductions [1]





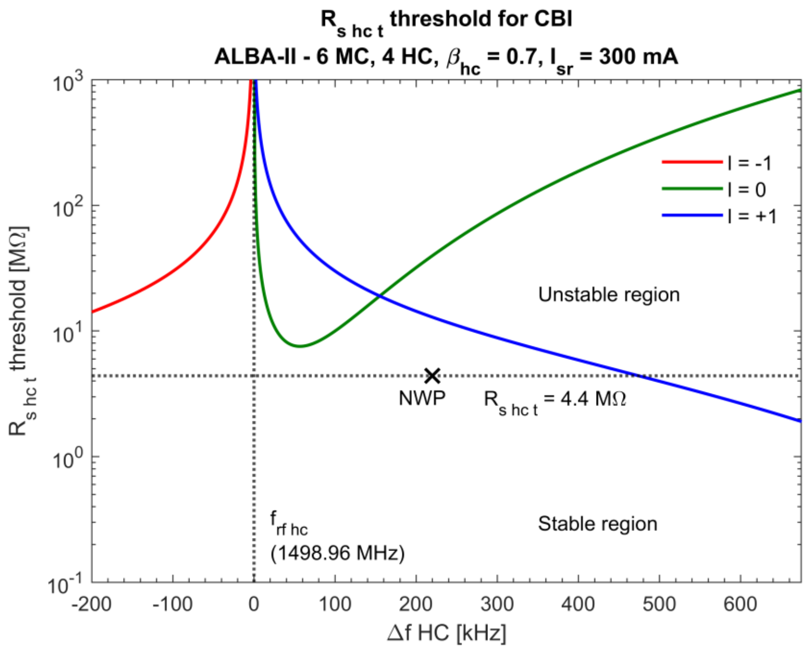
1. P. Solans et al., DOI: 10.18429/JACoW-IPAC2024-WEPR76

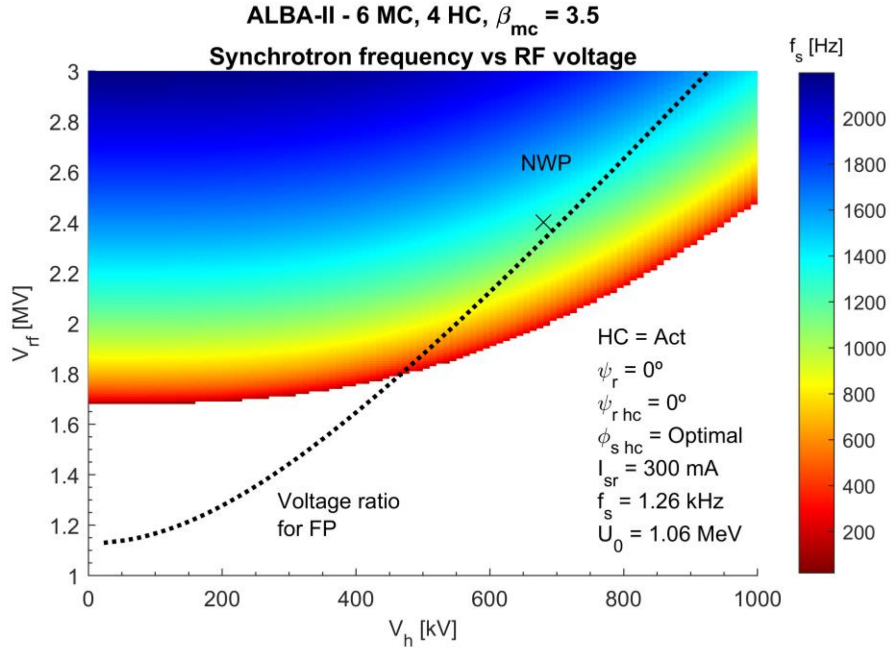
BEAM STABILITY STUDIES – DRFF



- DRFF was also tested at BESSY II with good results

BEAM STABILITY STUDIES





$$\tau^{-1} = \frac{e\alpha I}{4\pi E_0 \nu_s}\left\{\sum_{n=0}^{\infty} \omega_{\mu,n}^{+}\, Re\left[Z\left(\omega_{\mu,n}^{+}\right)\right] - \sum_{n=0}^{\infty} \omega_{\mu,n}^{-}\, Re\left[Z\left(\omega_{\mu,n}^{-}\right)\right]\right\}$$

$$f_s = f_{s0}\sqrt{1 - \frac{2\left(Z_i^0 + mZ_{i\ hc}^0\right) I_{sr}}{V_c \cos\phi_s}}$$

- Coupled bunch (CBI) and Robinson DC instabilities have been also studied analytically for ALBA II. Robinson DC has been cross-checked with experimental studies at ALBA

BEAM STABILITY STUDIES

A. Gamelin et al.: DOI: 10.1103/PhysRevAccelBeams.28.054401

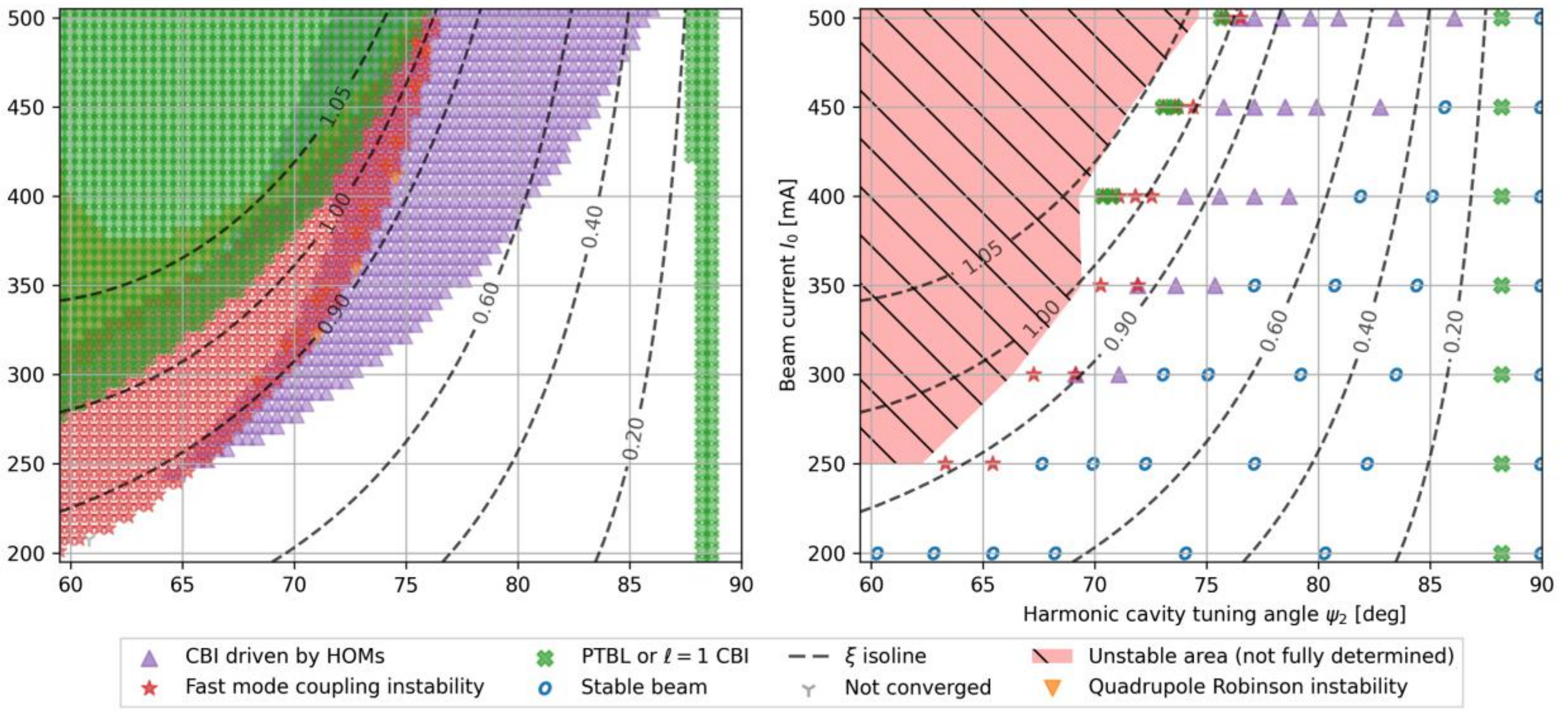
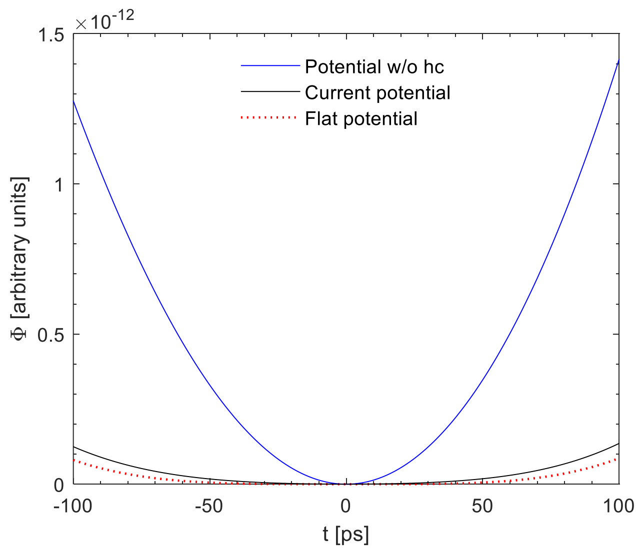


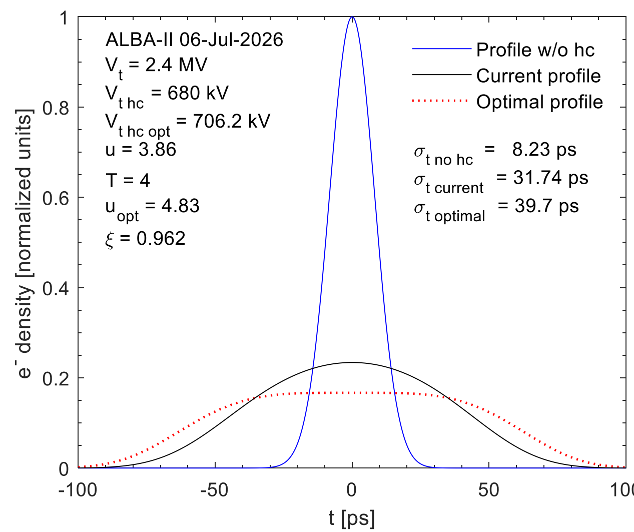
FIG. 3. Instabilities predicted for the SOLEIL II storage ring, with the Alves solver (left) and with tracking (right). A HOM is included with $f_{\mathrm{HOM}} = 1.7$ GHz, $Q_{0_{\mathrm{HOM}}} = 670$ and $R_{s_{\mathrm{HOM}}} = 8.8$ kΩ. Passive HC parameters: $R_{s_2}/Q_{0_2} = 60$ Ω, $Q_{0_2} = 31 \times 10^3$.

- As future work, we plan to generate **Bosch stability diagrams** for the double RF system operation (HC voltage vs current vs stability)

BEAM STABILITY STUDIES – Resulting lifetime

- With a homogeneous filling pattern (HFP), and the 4 x 3HCs, we expect to reach a **bunch lengthening factor of 3.9**, increasing the default 8.2 ps length to approximately 31.7 ps
- Under these conditions, and with full filling pattern, the Touschek lifetime would be then raised from **5.4 h** to around **21 h**
- By **implementing DRFF**, this lifetime enhancement factor could be **further improved** from 3.9 to close to 4.9, which corresponds to the theoretical maximum
- Intra beam scattering (IBS) effect has also been considered in these studies. It increases horizontal emittance, energy spread and bunch length in **less than 2%**





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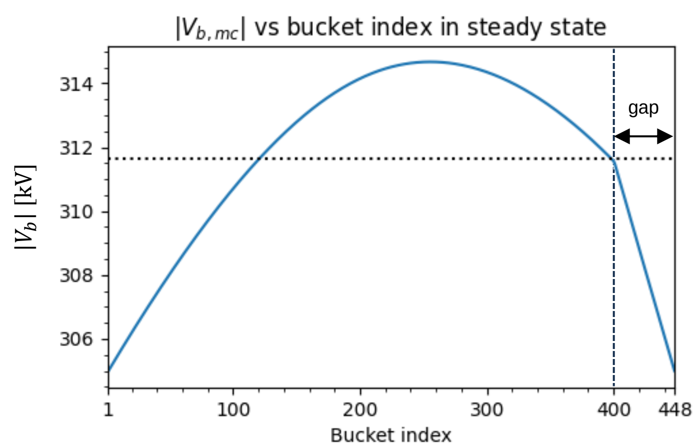
TRANSIENT BEAM LOADING (TBL)

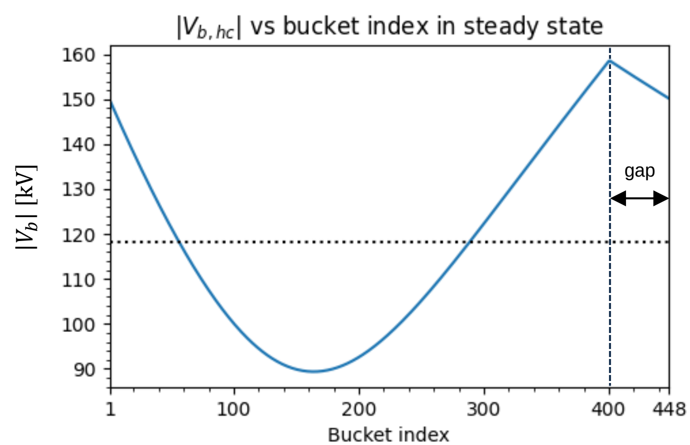
- In RF cavities, the **beam induced voltage** (the beam loading), V_b represents a considerable part of the total voltage, V_c. This contribution can be around the 40% in the MC and > 80% in the HC

- V_b is built on the **successive passage** of bunches. It reaches an **equilibrium** when the decay of the cavity voltage between bunch passages matches the voltage added by each bunch

$$V_b = -\left(\frac{1}{2}\,V_{b0} + V_{b1}\,e^{-\frac{t_1}{\tau_f}}\,e^{i\psi_1} + V_{b2}\,e^{-\frac{t_2}{\tau_f}}\,e^{i\psi_2} + \cdots\right) = -\frac{1}{2}\,V_{b0}\; - \sum_{l=1}^{N} V_{b0}\,e^{l(-\delta\,+\,i\psi)}$$

- **Uneven charge distribution** in the buckets, such as ion clearing gaps, break the homogeneous build-up causing a periodic modulation in the cavity voltage with a period equal to the revolution time





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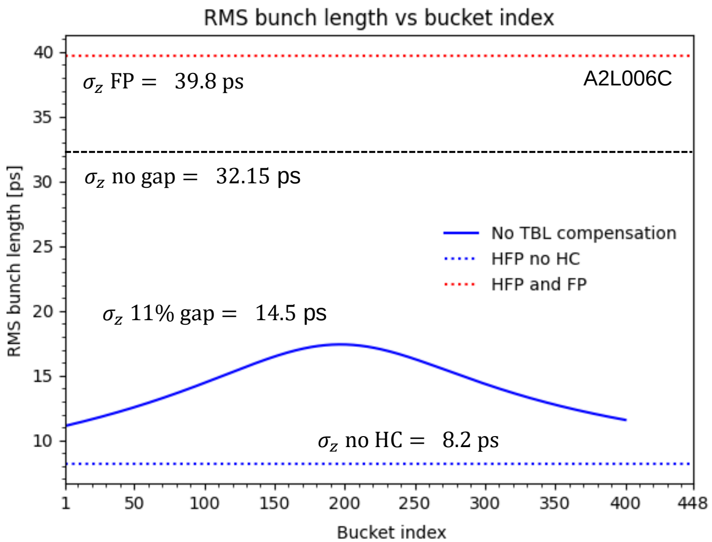
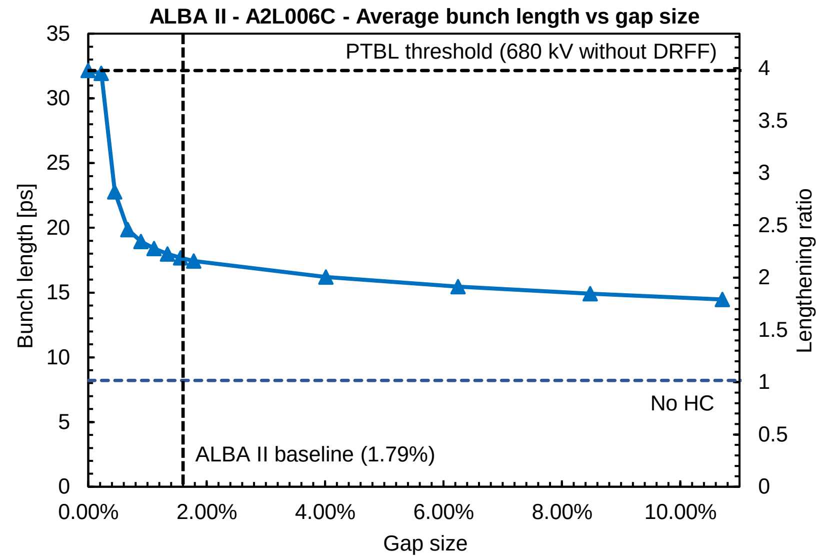




- The **different MC and HC voltages** seen by the bunches cause different bunch properties (synchrotron frequency, bunch length, phase, etc.) along the bunch train
- The bunch length, and thus the **Touschek beam lifetime**, is **specially affected** in the case of a double NC RF system tuned to maximize them
- Just a 2% gap can lead to Touschek lifetime reductions of about 45%
- A proper transient beam loading (TBL) calculation and **compensation** is therefore **highly advised** in case a gap in the beam is foreseen in a SR with a double RF system

TBL COMPENSATION - METHODOLOGY

- Taking advantage of the active HCs, it is possible to modulate the generator induced voltage $\tilde{V}_b$, to **counter** the modulation induced by the beam and get a flatter cavity voltage ($\tilde{V}_c$) :

$$\tilde{V}_c(t) - \tilde{V}_b(t) = \tilde{V}_g(t)$$

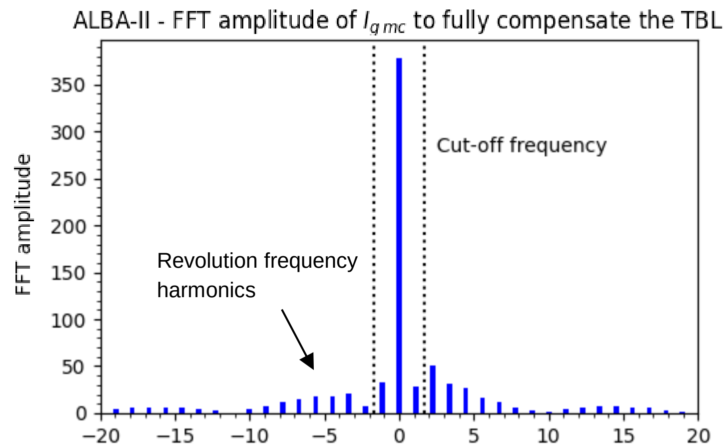
which gives us **the ideal generator voltage** to fully compensate the TBL. From this signal, I_g and then P_g can be then calculated [1]:

$$\tilde{I}_g(t) = \frac{1}{k_l}\left[\frac{d\tilde{V}_g(t)}{dt} + \frac{1}{\tau_f}[1 - i\tan\psi_d]\,\tilde{V}_g(t)\right] \longrightarrow P_g(t) = \frac{R_s\left|\tilde{I}_g(t)\right|^2}{8\beta}$$

- However, RF cavities have a **narrow bandwidth** and **do not accept well** the high frequency **components** of the modulated power required to fully compensate the TBL. A very **high generator** power is required for some buckets, far exceeding the available one, resulting in a high reflected power, as well
- Following the strategy proposed by [1], we **can filter out most of the high frequency components** to effectively mitigate the TBL effects with reasonable amounts of additional generator power

[1] Yamamoto et al., DOI: 10.1103/PhysRevAccelBeams.21.012001

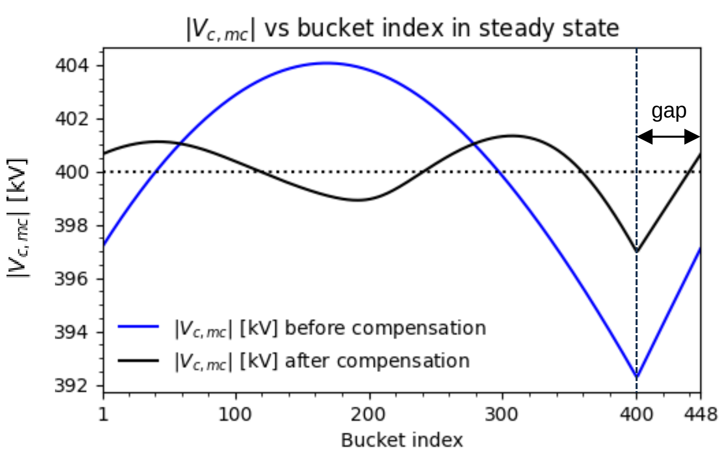
TBL COMPENSATION – METHODOLOGY

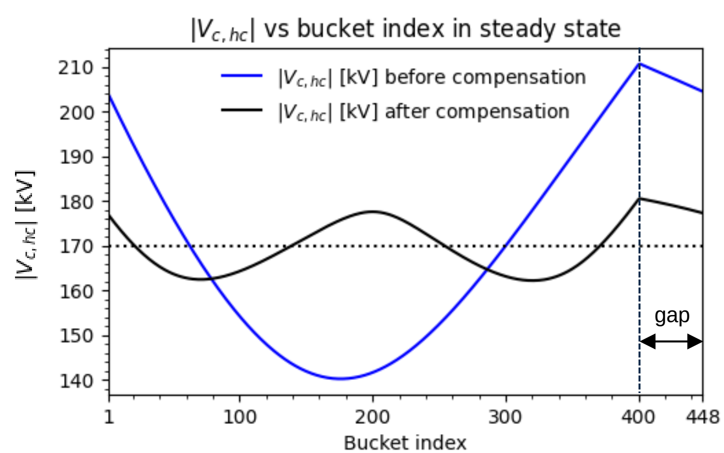


- After removing the **frequency components** higher than $\pm n f_c$, where f_c = f_{rev} (1.12 MHz for ALBA and ALBA II) we construct a new, filtered $\tilde{V}_g$:

$$\tilde{V}_g(t) = e^{\alpha(t-t_0)}\left[\tilde{V}_g(t_0) + k_l \int_{t_0}^{t} \tilde{I}_{g\,filt}\,(t')e^{-\alpha(t'-t_0)}dt'\right]$$

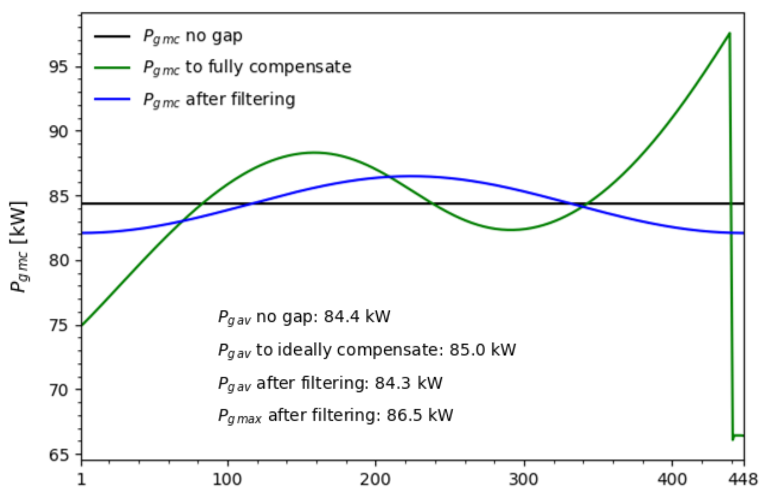
- The result is a **flatter cavity voltage**, both in amplitude and phase, for both the MCs and HCs, without requiring an unaffordable amount of RF power:

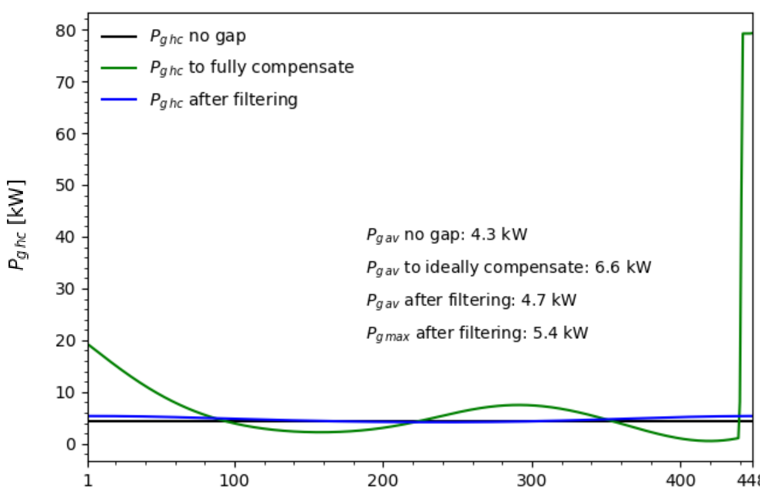




TBL COMPENSATION - ALBA II CASE

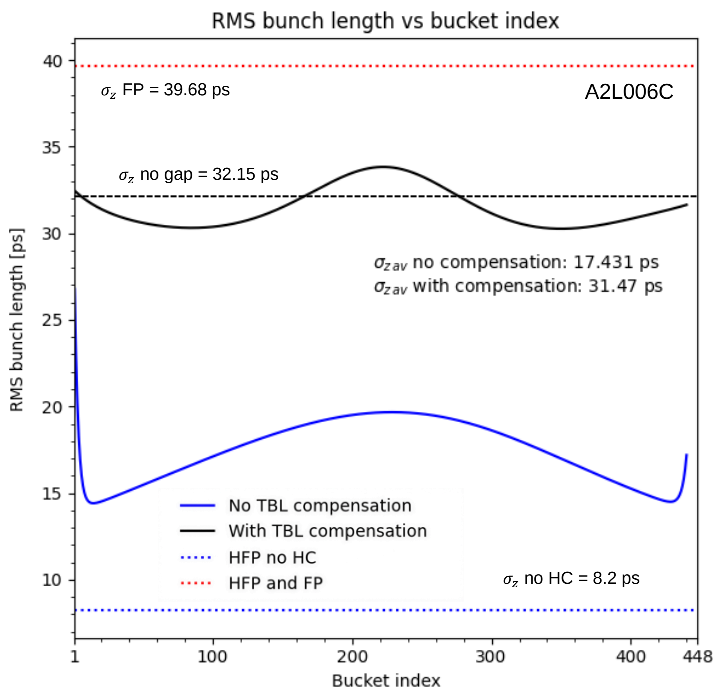
- For the ALBA II baseline scenario, full compensation of the TBL in the HCs would require **80 kW of SSPA power**, per harmonic plant
- By filtering the harmonics higher/lower than ±1 f_{rev}, the required power is only 1 kW above the no-gap case, reaching a maximum of **5.4 kW**
- With the proposed compensation scheme, and for small gaps, the average energy **consumption** should not be much higher than without compensation

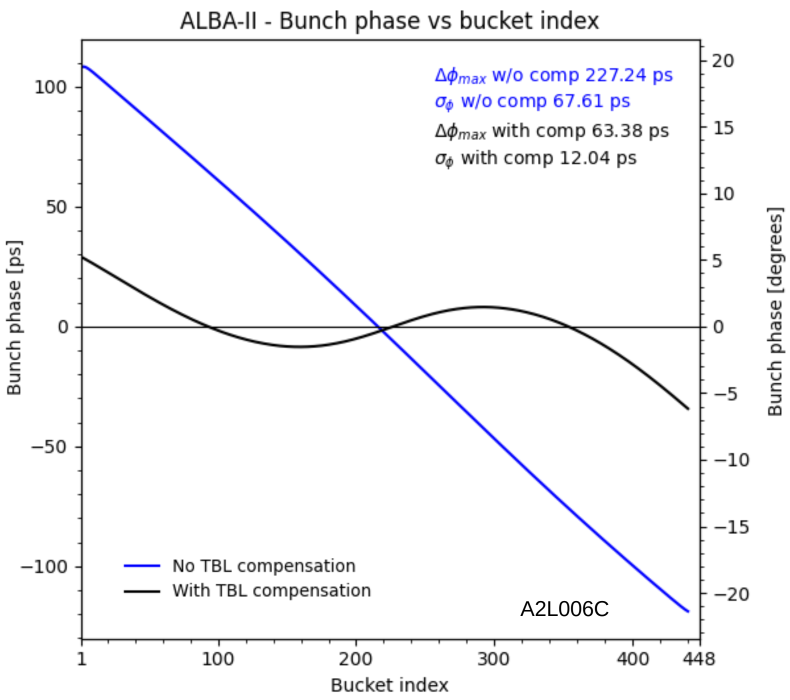




TBL COMPENSATION - ALBA II CASE

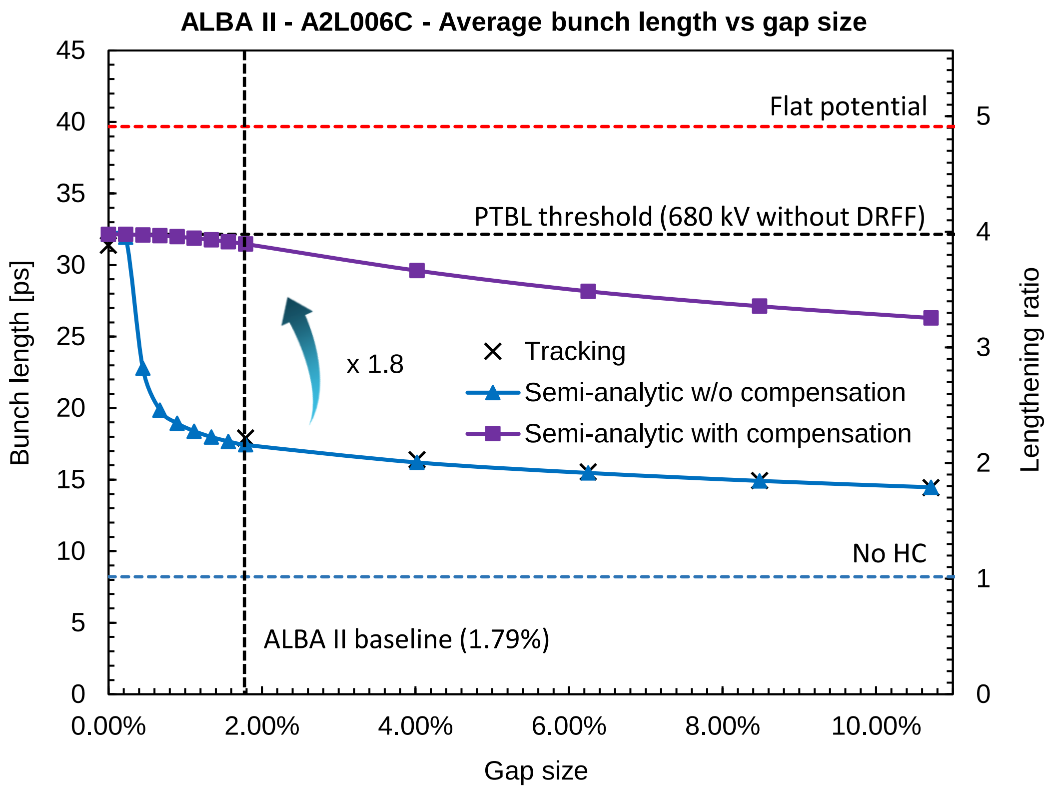
- In the ALBA II baseline scenario correcting only the 1st revolution harmonic in both MCs and HCs would yield a **very high compensation efficacy**, with a bunch length around 98% of the no-gap case
- With these settings the Touschek lifetime would be improved **from 11.5 h to 20.6 h**





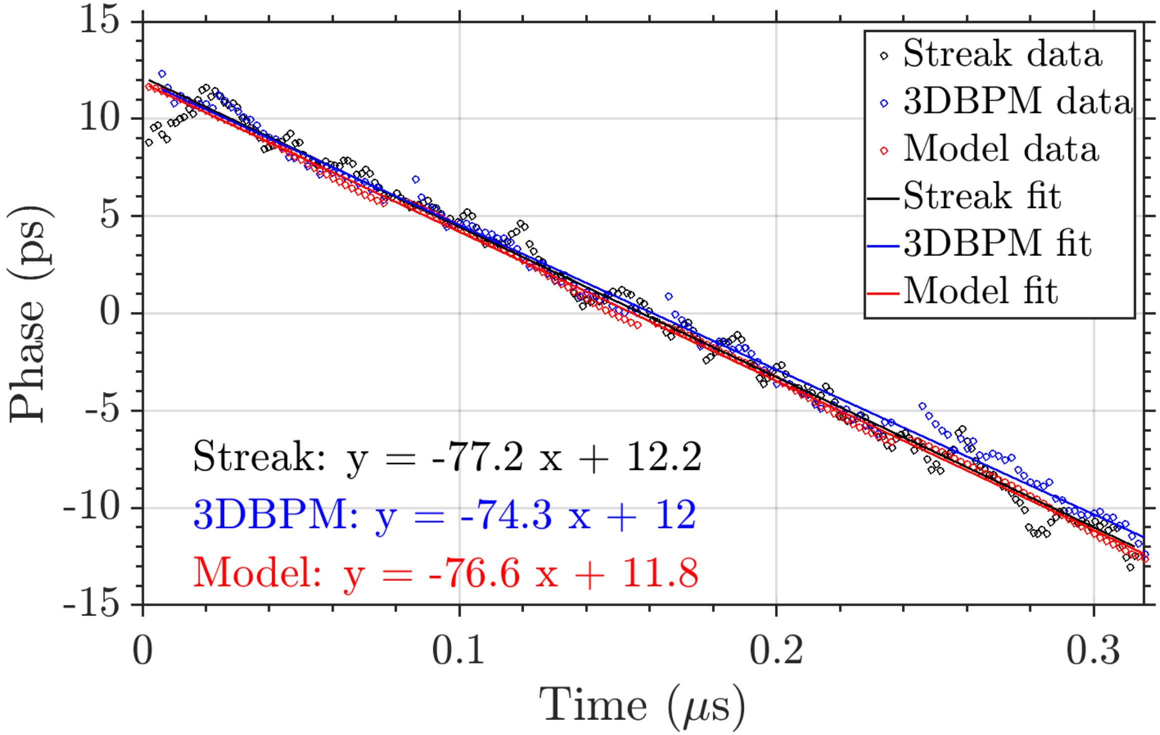
TBL COMPENSATION - ALBA II CASE

- Even if the 1.8% of gap has a **heavy impact** on the average bunch length, further increasing this value does not seem to worsen the impact on the average bunch length much
- For **gaps < 2%,** compensations higher than 90% should be **easily achieved**
- **Tracking** simulations with power modulation are planned as future work



TBL COMPENSATION - ALBA II CASE

- The phase offset as a function of bucket index obtained with the developed code has been **validated** against **experimental measurements** at ALBA using both the streak camera and the fast oscilloscope acquisition method, showing very good agreement



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ALBA II – Trip compensation system

- **Good beam availability** is an essential goal for ALBA II, as it is for ALBA
- The RF system of ALBA currently has around **10 RF interlocks** per month. So 10 potential beam losses due to RF
- When there is a **sudden loss of 400 kV** on RF voltage, combined with additional losses from an unexpected parasitic cavity, the beam transitions from one equilibrium phase to another. The resulting oscillation reduces the total voltage due to increased beam loading, which, at sufficiently high currents, can lead to **beam loss**
- At ALBA, we have a dedicated **Trip Compensation System (TCS)** which raises automatically the RF power and phase delivered to the cavities after a beam loss to **counter** the large beam **oscillations**. To mathematically simulate a trip, we have a **Simulink** model which includes longitudinal dynamics equations and a **RLC cavity** model. It has been compared with experimental results at ALBA, resulting in a **good match**

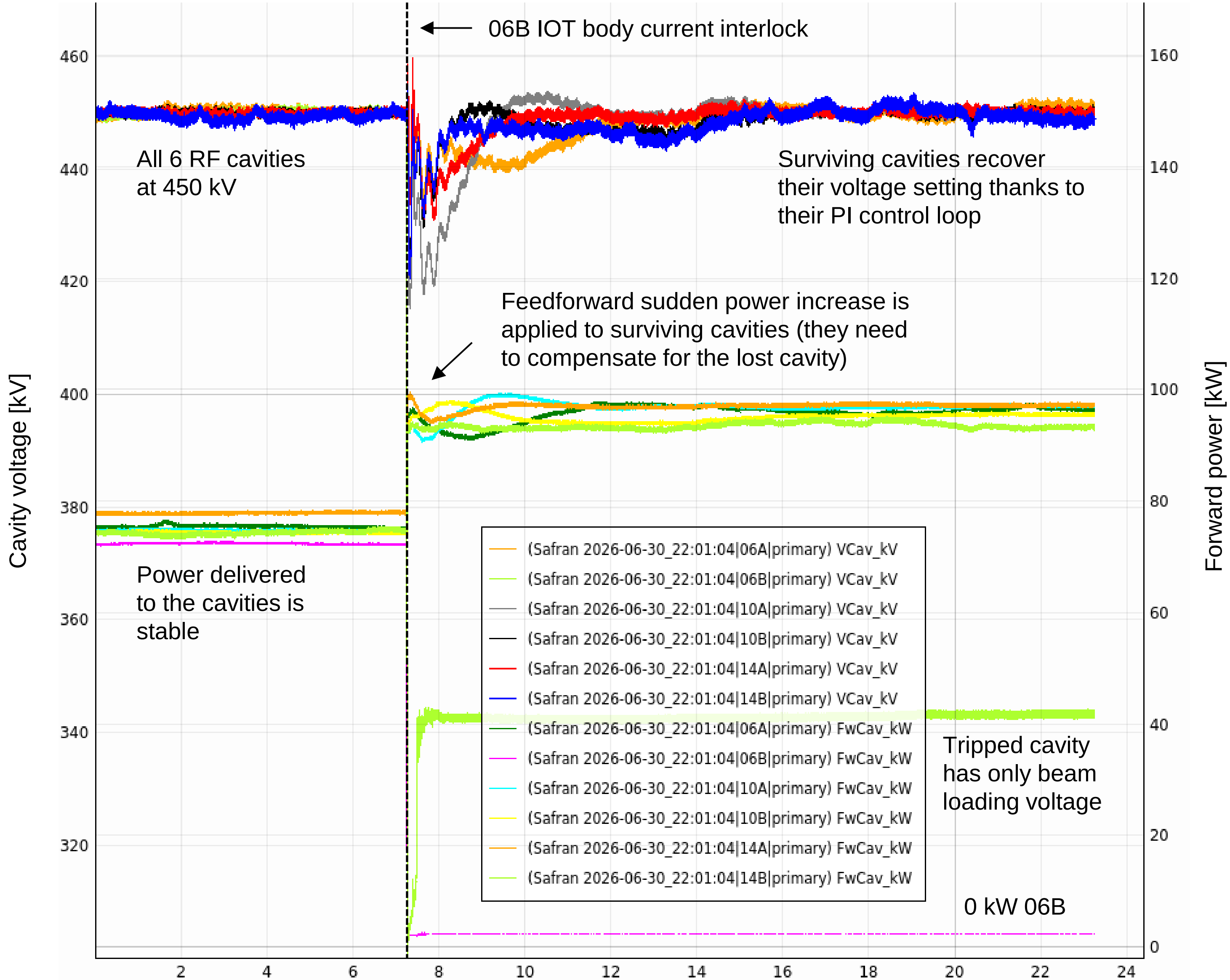
$$\dot{V}_r + \frac{\omega}{2\,Q_l} V_r + (\omega - \omega_{rf})\, V_i = \frac{\omega R_l}{2\,Q_l} \left(\widetilde{I_g} + \widetilde{I_b} \right)_r$$

$$\dot{V}_i + \frac{\omega}{2\,Q_l} V_i - (\omega - \omega_{rf})\, V_r = \frac{\omega R_l}{2\,Q_l} \left(\widetilde{I_g} + \widetilde{I_b} \right)_i$$

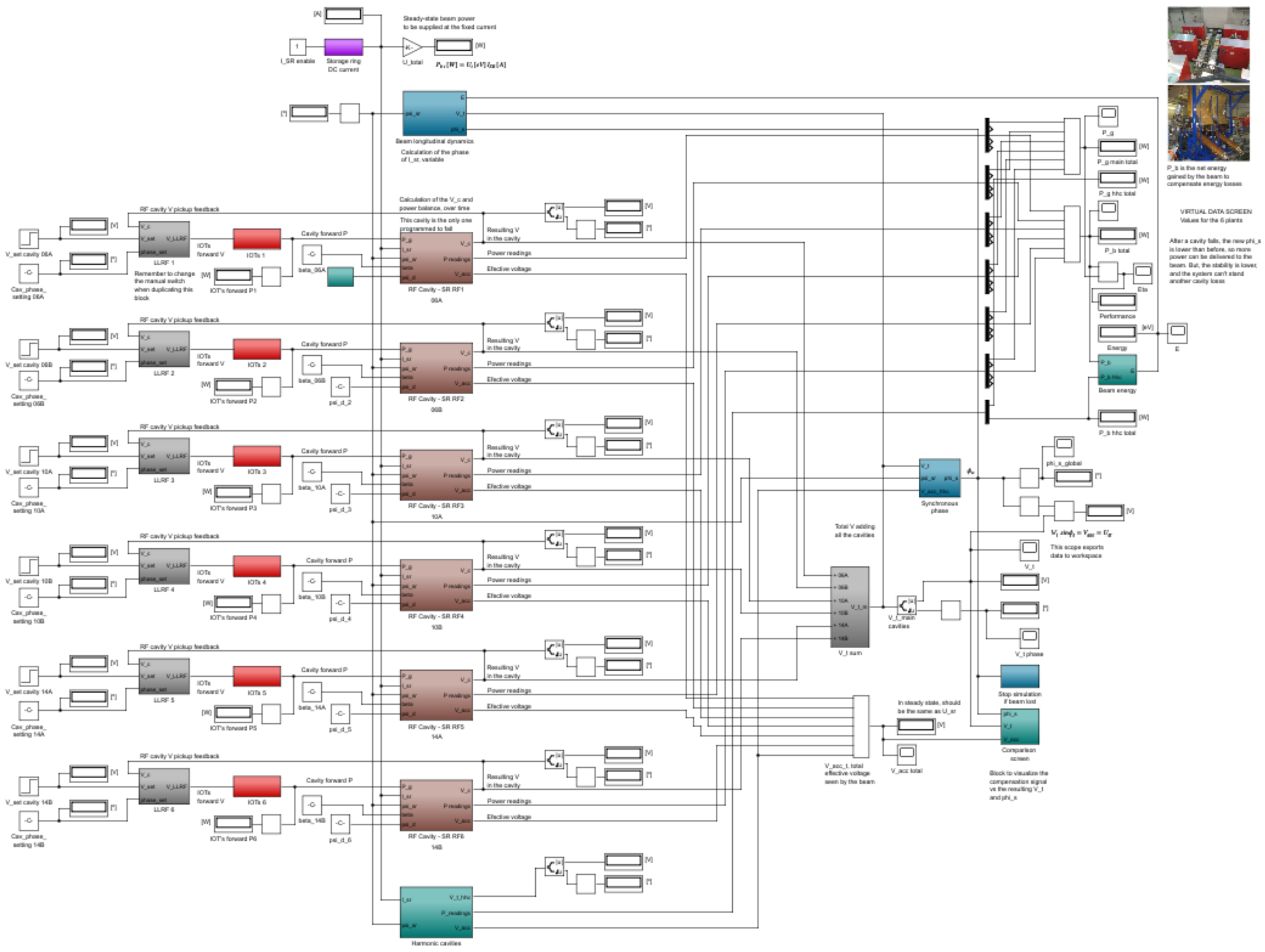
$$\frac{d^2\psi}{dt^2} + 2\alpha_\gamma \frac{d\psi}{dt} - \frac{\Omega_{s0}^2}{\cos\phi_s} (\sin\phi - \sin\phi_s) = 0$$

$$\phi = \frac{\pi}{2} - \psi + \psi_{V\,t}$$

ALBA II – Trip compensation system



ALBA II – Trip compensation system



ALBA II – Trip compensation system

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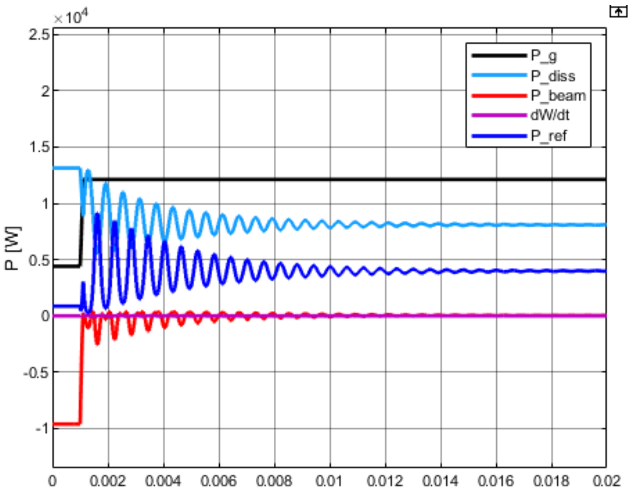
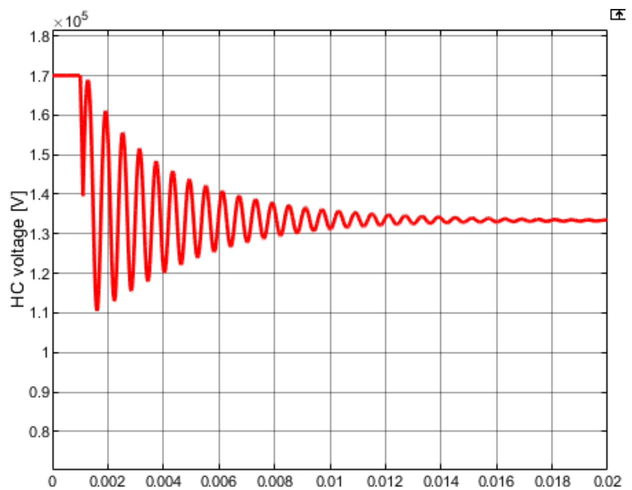


HC power balance after a MC trip



HC voltage amplitude after a MC trip

OUTLINE

- Introduction: ALBA and ALBA II Light Sources
- ALBA II RF system: Overview, new developments
- Beam stability studies: Expected instabilities, tracking simulations, Direct RF Feedback
- Transient beam loading (TBL): Expected impact, foreseen solutions
- Trip compensation system (TCS): Simulations and experimental results
- Summary

GENERAL SUMMARY

- **Beam stability** studies via particle **tracking** (elegant, mbtrack2) and analytical models are used determine bunch lengthening efficiency of the new 3HC system, both in ALBA and ALBA II
- These studies have predicted **onset of PTBL instabilities** above flatness factor $\xi = 0.96$, limiting the HC voltage to 680 kV (being the flat potential at 706 kV) and the **bunch lengthening factor to 3.9**
- The use of **Direct RF Feedback** would improve the bunch lengthening performance of the double RF system and allow a lower main voltage setting in ALBA II.
- **Transient beam loading** due to ion clearing gaps has been studied. It has **large impact on the lengthening performance** of the double RF system of ALBA II, even for very small gaps, being able to decrease the resulting Touschek lifetime in **more than 40%**
- The calculations indicate that this effect can be **effectively mitigated in the ALBA II storage ring** by applying a **feedforward amplitude modulation** of the power delivered to both MCs and HCs at the revolution frequency, without the need of additional hardware, achieving bunch lengthening factors of **more than 90%** of the full filling pattern case
- The **trip compensation** system studies predict that the current strategy can also be used for ALBA II, allowing the **beam** to **survive** when either a main or an harmonic cavity are lost. However, a feedforward signal must be applied on both RF systems

FUTURE MACHINE STUDIES SUMMARY

- During 2027 onwards, we will be conducting a series of machine studies to improve the performance of the double RF system, for both ALBA and ALBA II:
  - ✓ Double RF system intrinsic instabilities mitigation (such as PTBL) by means of DRFF
  - ✓ Beam lifetime increase vs flatness factor/HC voltage
  - ✓ 3HC passive operation, as a back-up plan in case of a transmitter fail
  - ✓ TBL compensation, by means of forward power modulation
  - ✓ TCS studies, both to guarantee the beam stability after a MC and HC trip and to be able to lower the main MC voltage in ALBA II
  - ✓ Ion effects vs gap size, already under study at ALBA

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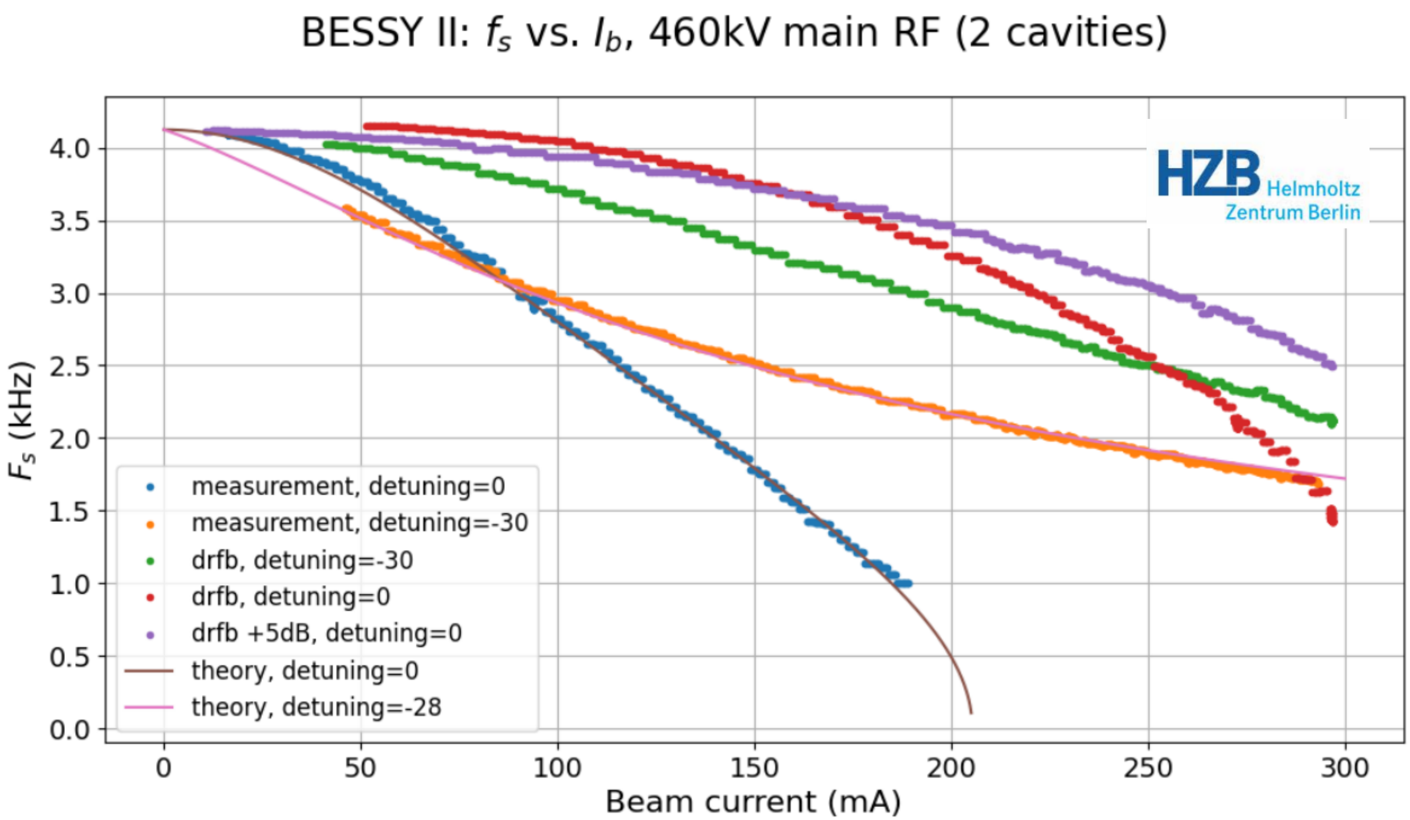
EXTRA SLIDES

BEAM STABILITY STUDIES – DRFF



- DRFF was also tested at BESSY II with good results

TBL ALGORITHM STEPS

0. HC complex voltage setting calculation. Initially form factor (FF) = 1 and all bunch phases = Φ_s

1. Beam loading build-up/decay depending on **FF and bunch phase**

$$\tilde{V}_{b,i} = \tilde{V}_{ba,i-1} e^{-\delta_l + j\psi_t} - k_l \tilde{F}_{n,i} q_i$$

2. Total cavity voltages along the bunch train. Adjust average generator voltage and tuning. Modulate generator current to **compensate TBL**

$$\tilde{V}_c(t) = \tilde{V}_{g\,filt}(t) + \tilde{V}_b(t)$$

3. RF potential and longitudinal bunch charge distribution along the bunch train

$$\Phi(\varphi) = -\frac{c\alpha_c}{EC\omega_{rf}} \int_0^{\varphi} (eV_t(\varphi') - U_0)\, d\varphi' \qquad \rho(\varphi) = \bar{\rho} e^{-\frac{\Phi(\varphi)}{\alpha_c^2 \sigma_\epsilon^2}}$$

4. Complex FF and bunch phase

$$\tilde{F}_n = F_n e^{j\phi_{F,n}} = \frac{\mathcal{F}[\rho(t)]_{\omega = n\omega_{rf}}}{|\mathcal{F}[\rho(t)]_{\omega=0}|}$$

Iterate until convergence (steps 1–4)

5. Individual and average bunch length and Touschek lifetime

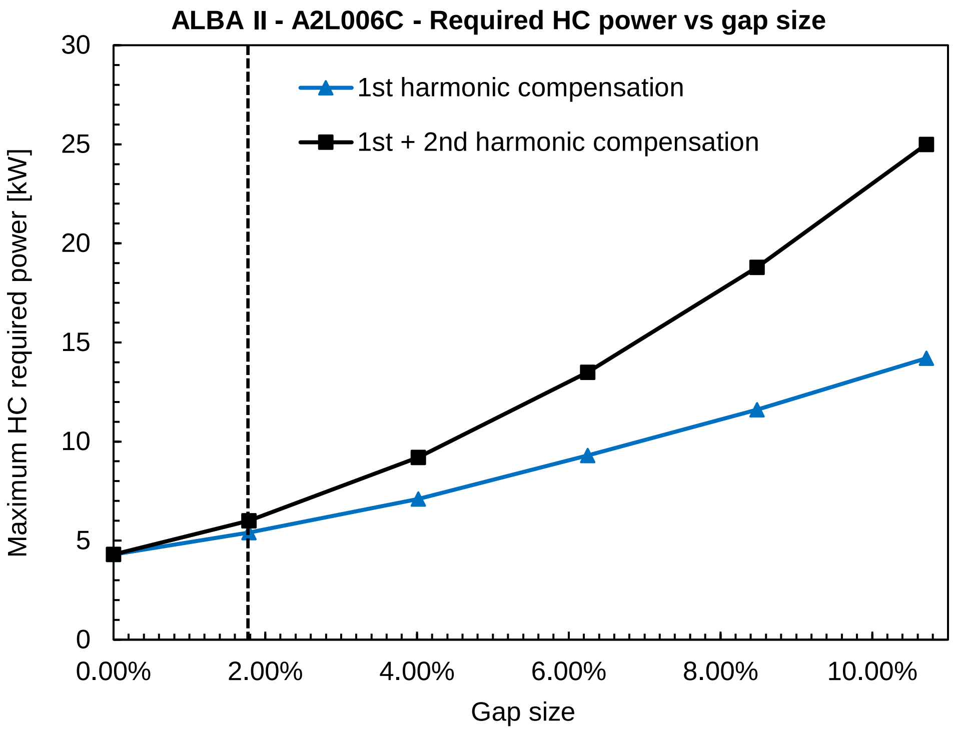
$$\sigma = \sqrt{\int_{\varphi_l}^{\varphi_r} (\varphi - \bar{\varphi})^2 \rho(\varphi)\, d\varphi}$$

6. MC/HC Power balance

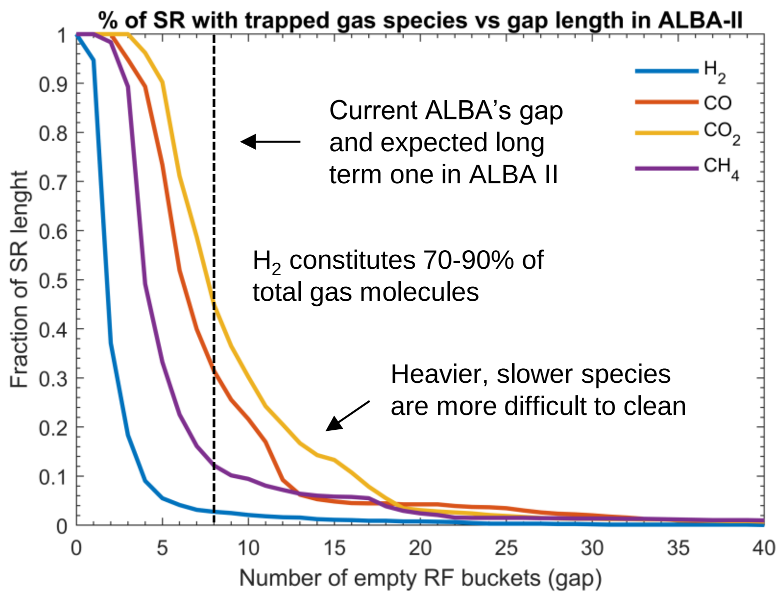
$$P_g(t) = \frac{R_s \left|\tilde{I}_g(t)\right|^2}{8\beta}$$

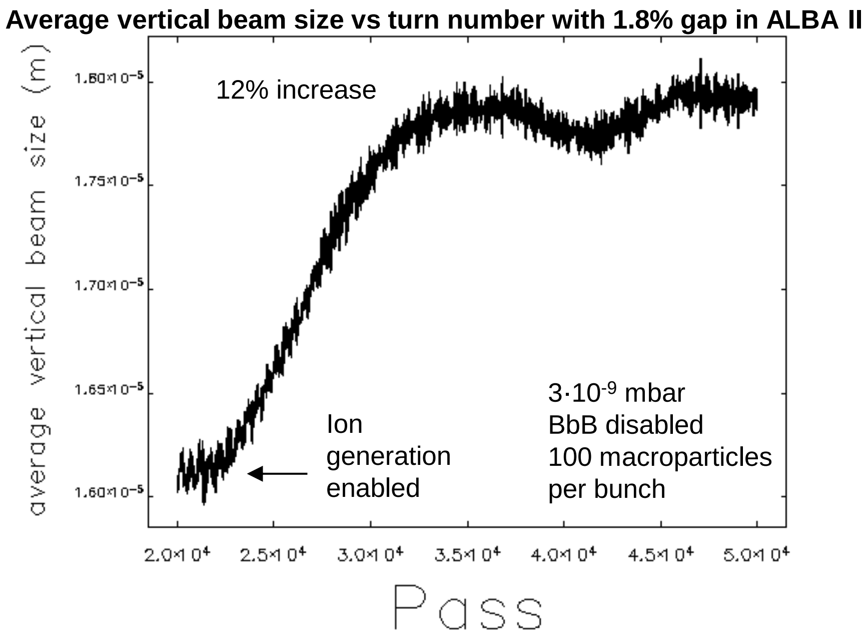
TBL COMPENSATION - ALBA II CASE

- The **higher the gap size**, the higher the amount of power required to optimally mitigate the ±1 f_{rev} components
- Compensating the 2nd harmonic components and beyond is **not recommended** if not using dedicated broadband cavities, given the low efficiency that they entail



ION EFFECTS STUDIES





- To determine the necessary ion clearing gap length for ALBA II, we have been conducting **beam-ion instability studies**
- The main concern is the **beam size blow-up** caused by accumulated ions, particularly during early commissioning when the synchrotron radiation-induced gas density is high
- Early simulation results suggest that **a single 1.8% clearing gap** combined with a bunch-by-bunch (**BbB**) feedback system should be **sufficient** to keep the beam size growth within acceptable limits

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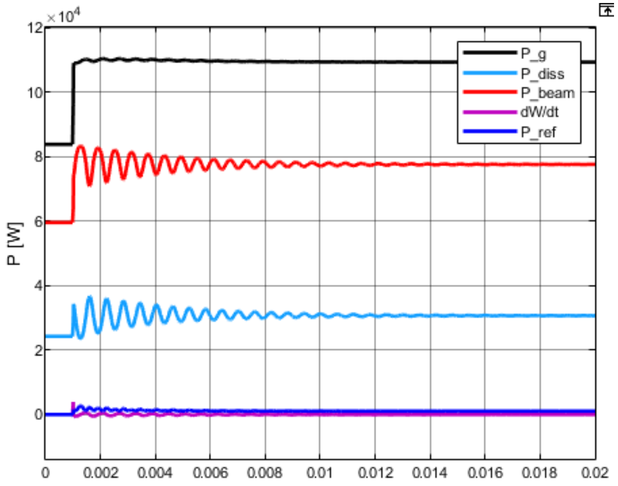
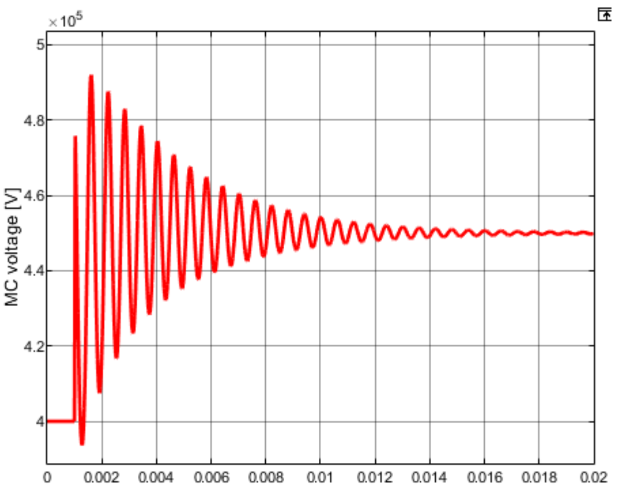


Active MC power balance after a MC trip



Active MC voltage amplitude after a MC trip

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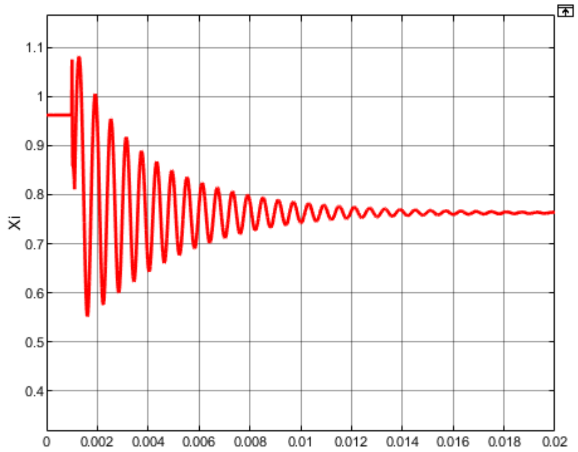

Flatness factor (ξ) after a MC trip

$$\xi = \frac{-mV_{hc}\cos\phi_{s,hc}}{V_{mc}\cos\phi_{s,mc}}$$

CONSTANT POWER PHASE LOOP

- Taking into account that most of the harmonic cavity voltage content is driven by the beam itself and that the phase must follow the beam, the **Constant Power Phase Loop** has been implemented in the DLLRF
- The loop monitors the **amplitude of the cavity** and adjust the phase of the drive to compensate, thus resulting in a beam phase control loop